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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF PHYSICAL AND COMBUSTION
PROPERTIES OF SEVERAL RESIDUAL FUEL OILS AND
MAGNESIUM - FUEL-OIL SLURRIES IN A RAM-JET-
TYPE COMBUSTOR

By Preston N. Cook, Jr., Vernida E. Evans, and
Erwin A. Lezberg

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Cleveland, Ohio

**NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS**

WASHINGTON

June 23, 1953

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SEVERAL RESIDUAL FUEL OILS AND MAGNESIUM - FUEL-OIL SLURRIES
IN A RAM-JET-TYPE COMBUSTOR

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SUMMARY

An experimental investigation was conducted with a $1\frac{7}{8}$ -inch-diameter burner to determine the suitability of residual fuel oils as carriers in magnesium slurries. The residual-fuel-oil slurries were compared to slurries containing MIL-F-5624A grade JP-4 fuel stabilized with petro-latum or gel with respect to combustion efficiency, blow-out velocity, and stability of the magnesium-hydrocarbon suspension. Four residual fuel oils having viscosities of 5 to 415 centipoises were investigated by themselves and in slurries of 50 percent magnesium having viscosities from 22 to 8050 centipoises.

The blow-out velocities of the fuel-oil slurries were lower than those of the petro-latum- or gel-stabilized JP-4 slurries. Fuel-oil slurries containing 2-micron powder had much higher blow-out velocities than fuel-oil slurries made with 13-micron powder.

All the 13-micron-magnesium-powder slurries with fuel oil or JP-4 carriers had substantially the same metal and hydrocarbon combustion efficiencies over a range of equivalence ratios. The 2-micron-powder slurry, although burned at four times the inlet air velocity of the 13-micron-powder slurries, showed a slightly higher metal combustion efficiency.

Neither the fuel oils by themselves nor the slurries made with the two lower-viscosity oils required preheating for combustion using the air atomizing nozzle, while the slurries made with the two more viscous fuel oils could be burned only when preheated to a temperature approaching 212° F.

Slurries made with 2-micron powder in each of the fuel oils and with 13-micron powder in the two more viscous fuels oils were sufficiently stable to be usable for at least 48 hours. Slurries made with the 13-micron powder in the two lower-viscosity oils were unstable; that is,

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they settled out within 48 hours and needed agitation before they could be used.

INTRODUCTION

The use of metal-hydrocarbon slurries as fuels in jet-engine propulsion systems has been the subject of analytical and experimental investigations at the NACA Lewis laboratory. As a result of these investigations, substantial improvements in air specific impulse and operational limits have been realized in an experimental small-scale afterburner by the addition of magnesium powder to conventional hydrocarbon fuels (ref. 1). In reference 2, it is shown that, in an afterburner operating with water injection, a magnesium slurry can be burned at a much higher water-air ratio than was possible with JP-3 fuel.

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The higher air specific impulse of the metal-hydrocarbon slurry over the hydrocarbon alone is due mainly to the higher heat of combustion per pound of air of the slurry compared at the same equivalence ratio. Reference 3 reports the results of analytical investigations in which the equilibrium composition and the temperature of the combustion products were determined for octene-1 and for aluminum - octene-1, magnesium - octene-1, and boron - octene-1 slurries when burned in air. Values of theoretical air specific impulse for octene-1 and the slurries were computed and are shown to be higher for each of the slurries than for the hydrocarbon.

The results of an experimental investigation to determine how the metal and the hydrocarbon separately contribute to the over-all combustion of magnesium and boron slurries burning in a $1\frac{7}{8}$ -inch-diameter burner are reported in reference 4. The combustion efficiency (ratio of energy released to energy available by complete combustion) of the magnesium-powder component of slurries was only slightly decreased by oxygen depletion as fuel-air ratio was increased above stoichiometric, whereas the combustion efficiency of the hydrocarbon portion of the slurry declined rapidly.

Results of an investigation to determine the effects of particle size and stabilizing additives on the combustion efficiency and the blow-out velocity (burner-inlet velocity at which flame failure occurs) of magnesium-hydrocarbon slurries are reported in reference 5. Slurries with petrolatum (a high-boiling viscous fraction of petroleum) as a stabilizing additive had combustion properties comparable with the gel-stabilized slurries. The combustion efficiency of the magnesium in the slurry was improved by the use of powder of smaller particle size. The smaller-particle-size slurry could be burned to a leaner mixture limit and at higher combustion velocities than the hydrocarbon alone or slurries containing the larger magnesium particles.

To date, the magnesium-powder industry has not been able to furnish adequate quantities of magnesium powder fine enough to remain suspended in JP-4 fuel without the use of a stabilizing additive. The increased stability of slurries containing residual fuel oils without additives over those containing JP fuels and the general availability of these fuel oils make them attractive for use in slurry fuels.

The object of this investigation was to determine the physical and combustion properties of magnesium slurries prepared with residual fuel oils.

Combustion efficiencies and blow-out velocities were determined in a $1\frac{7}{8}$ -inch-diameter burner for magnesium slurries made with residual fuel oils and with MIL-F-5624A grade JP-4 fuel stabilized with either petrolatum or previously unreported gelling agent. Blow-out velocities of the fuel oils alone were also determined. The slurries contained 13- or 2-micron powder. The combustion efficiencies of the metal and of the hydrocarbons were evaluated separately by sampling and analyzing the gaseous and solid combustion products. The stability and the viscosity of each slurry were also determined.

The experimental work was done at the NACA Lewis laboratory from November 1952 to February 1953.

SYMBOLS

The following symbols are used in this report:

CO_2/C	molecular weight ratio of CO_2 to C when C burns to CO_2
CO_2/CO	molecular weight ratio of CO_2 to CO when CO burns to CO_2
H/C	hydrogen-carbon weight ratio
h_{CO}	heat of combustion of carbon to carbon monoxide, Btu/lb CO
h_{CO_2}	heat of combustion of carbon to carbon dioxide, Btu/lb CO_2
$h_{\text{H}_2\text{O}}$	heat of combustion of hydrogen to water (lower value), Btu/lb H_2O
h_0	total liquid-slurry height at zero time
h_t	metal-liquid-phase height at time t

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W_C	weight of solid carbon in combustion sample ^a
W_{CO}	weight of carbon monoxide in combustion sample ^a
W_{CO_2}	weight of carbon dioxide in combustion sample ^a
W'_{CO_2}	weight of carbon dioxide formed by catalytic combustion of gaseous hydrocarbon residues in combustion sample ^a
W_{H_2O}	weight of water in combustion sample ^a
W'_{H_2O}	weight of water formed by catalytic combustion of gaseous hydrocarbon residues on combustion sample ^a
W'_M	weight of uncombined metal in combustion sample ^a
W_{mo_x}/W_m	molecular weight ratio of metal oxide to metal
W_S	weight of solids in combustion sample ^a
η_{HC}	combustion efficiency of hydrocarbon
η_M	combustion efficiency of metal
ϕ	equivalence ratio

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APPARATUS AND PROCEDURE

Combustor and Operating Procedure

The slurry burner and the exhaust-sampling apparatus are shown in figure 1. The burner consisted of a $1\frac{7}{8}$ -inch-inside-diameter tube 20 inches long. A tube liner with an outside diameter of $1\frac{5}{8}$ inches, a thickness of $1/16$ inch, and a length of 2 inches was mounted at the inlet, providing a small primary zone through which the atomized fuel was introduced. Secondary air was introduced as an annular stream along the burner wall. The secondary-air inlet was about one inch from the burner inlet.

The slurry was atomized and injected into the burner with a conventional paint-spray gun of the type that pressurizes the fluid. The spray nozzle was sealed to the burner inlet. The flow rate of the fuel

^aThe combustion sample was the total of gas and solids drawn through the sampling probe.

was set by a valve on the spray gun and was measured by weighing the spray gun before and after the timed flow interval. The flow of the air entering the burner was regulated with a throttling valve and was measured with a rotameter. The burner was ignited by opening the seal between the gun and the burner and holding an acetylene torch to the opening. Where it was necessary to preheat the fuel, the spray gun with the fuel was set into a container of boiling water.

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Sampling apparatus and procedure. - The sampling-probe assembly consisted of a 1/4-inch-outside-diameter copper tube incased in a water jacket. The outer wall of the jacket was covered with asbestos insulation. The 1/4-inch copper tube was connected to a solids-sampling tube which was packed with glass wool to collect the metal oxide, unburned metal, and carbon particles. The assembly was so mounted that it could be swung into the path of the flame, as indicated in figure 1. A rubber stopper sealed the opening of the probe. It was held in place by atmospheric pressure when the sampling apparatus was evacuated. As the probe moved toward the center of the burner outlet, the stopper was brushed off by the edge of the burner, thus permitting the exhaust gases and solids to be drawn in.

A 30-gallon vacuum tank was evacuated by the vacuum pump to about 1 inch of mercury absolute. The valve between pump and tank was closed while a sample was taken. The pressure in the tank was measured with a mercury manometer. A coil of copper tubing packed in powdered dry ice served to remove the moisture from the gases entering the vacuum tank.

The exhaust-gas sample was collected in the gas-sampling tube as follows: Both valves on the gas-sampling tube were open when the sampling began, the downstream valve was closed after about 20 seconds of burning operation, and then the upstream valve was closed after the pressure in the sampling tube had risen to atmospheric.

Test procedure. - For the combustion-efficiency tests the air flow was adjusted to give an inlet-air velocity of 22 feet per second for the 13-micron slurries and 80 feet per second for the 2-micron slurries. The velocity was increased for the latter fuels because the finer particles burned with high efficiency over the entire range of equivalence ratio, and it was necessary to create more severe burner conditions to distinguish the regions of lowered efficiency.

For the investigation of blow-out limits, the air flow was set below the blow-out velocity of the fuel mixture and gradually increased until flame failure occurred. This velocity (at flame failure) was taken as the blow-out limit.

Method of analysis. - The quantity of the combustion sample referred to in subsequent definitions includes all combustion products drawn

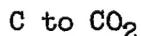
through the sampling probe. It is computed from the composition of the gases in the sample tube, the pressure rise in the vacuum tank, and the weight of the sample of solids.

By analysis of the solid and gas samples, the weights of the following constituents of the combustion sample were determined: N_2 , CO_2 , CO , H_2O , total solids, carbon, uncombined metal, and CO_2 and H_2O formed by catalytic combustion of unburned residues in the gas sample.

The composition of the gaseous products was determined with an Orsat apparatus equipped with a catalytic heater for the combustion of hydrocarbon residues. The amount of uncombined magnesium in the solid samples was determined by introducing an acid solution into the solids-sampling tube and measuring the volume of hydrogen evolved. The solids-sampling tube was weighed before the sampling, washed with distilled water after the acid treatment, dried, and weighed again. The gain in weight was taken as solid carbon. The nitrides in the solid samples were found to be less than 0.1 percent and were neglected. No carbonates were found in the solids.

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Combustion efficiency. - The combustion efficiencies reported herein are not based upon chemical equilibrium of the products of combustion, inasmuch as data are not available for the various species involved. Instead, for 100-percent combustion efficiency, the components were assumed to oxidize as follows:



The combustion efficiency of the metal is defined as

$$\eta_M = \frac{[W_S - (W'_M + W_C)]}{[W_S - (W'_M + W_C)] + W'_M \frac{W_{MOX}}{W_m}}$$

The combustion efficiency of the hydrocarbon is defined as

$$\eta_{HC} = \frac{W_{CO_2} h_{CO_2} + W_{CO} h_{CO} + W_{H_2O} h_{H_2O}}{\left(W_{CO_2} + W_{CO} \left(\frac{CO_2}{CO} \right) + W'_CO_2 \right) h_{CO_2} + (W_{H_2O} + W'_H_2O) h_{H_2O} + W_C \left(\frac{CO_2}{C} \right) h_{CO_2}}$$

Combustion efficiencies so defined are in substantial agreement with the conventional combustion efficiency at and below an equivalence ratio of unity. At equivalence ratios higher than unity, the combustion efficiencies do not account for deficiency of oxygen, as they are based only on the utilization of fuel.

²⁸⁸⁹ Spray photographs. - The photographs showing the spray droplets were made with the apparatus shown in figure 2. Light duration was 4 microseconds. The camera lens was $7\frac{1}{2}$ -inch Aero-Ektar f 2.5 and a Super Pan-chromatic Press film was used.

Fuels and Fuel Properties

The following fuels were used in this investigation:

Fuel	Magnesium average particle size, microns	Magnesium, percent by weight	Carrier fluid (a)	Additive		Viscosity at 30° C, centipoises	Stability ^b at 48 hr	Surface tension, dynes/cm
				Type	Percent			
I	--	0	Fuel oil 4A		0	5.0		33.4
II	13	50	Fuel oil 4A		0	22.0	0.582	
III	2	50	Fuel oil 4A		0	4200	0.984	
IV	--	0	Fuel oil 4		0	18.0		32.6
V	13	50	Fuel oil 4		0	75	0.572	
VI	2	50	Fuel oil 4		0	1450	0.986	
VII	--	0	Fuel oil 5		0	160		35.2
VIII	13	50	Fuel oil 5		0	720	0.960	
IX	2	50	Fuel oil 5		0	8050	1.000	
X	--	0	Fuel oil 6		0	415		35.9
XI	13	50	Fuel oil 6		0	1610	0.985	
XII	13	50	JP-4	Petrol- atum	24	4000	0.995	
XIII	13	50	JP-4	Gel	0.4	22,750	0.990	

^aFuel oil 4A is a Standard Oil of Ohio designation; fuel oils 4, 5, and 6 are A.S.T.M. designations.

^bRatio of the settling height of powder at 48 hr to initial height.

The particle-size designations used herein to describe the powders were determined with a Fisher Sub-Sieve Sizer. This instrument employs the air permeability method for measuring the average particle size of a powder.

The gelling agent was a proprietary preparation designated E-4. It was found to be superior to the aluminum octoate described in references 4, 5, and 6 in that no heating was required in preparing the gels and the viscosity was more nearly reproducible, but the gels prepared with E-4, like those prepared with aluminum octoate broke down (decreased in viscosity) with age.

The petrolatum stabilizer used in the slurries conformed to the following manufacturing specifications:

Melting point (Saybolt), °F	150-160
Penetration (A.S.T.M.)	140
Viscosity (Saybolt), sec at 210° F	90-100

By analysis, it was found that the hydrogen-carbon ratio (H/C) was 0.160 and the lower heat of combustion, 18,400 Btu per pound.

The method of determining slurry stability is completely described in reference 6. Immediately after a slurry was mixed, it was poured into a 29- by 150-millimeter flat-bottomed glass test tube to a height of about 6 inches, stoppered, and placed in a rigid test-tube rack. The liquid and the metal-liquid levels were measured with a cathetometer at intervals.

The values of surface tension were obtained by the ring method with a calibrated precision tensiometer. All measurements were made at room temperature, and one platinum ring was used for all the readings.

The viscosities were determined with a Synchro-lectric viscometer made by Brookfield Engineering Laboratories. The measurements were all made at 30° C at a spindle speed of 12 rpm, 30 seconds after the spindle was started. The spindle speed and timing for taking the viscosities were held constant, because the slurries are non-Newtonian.

RESULTS AND DISCUSSION

Settling characteristics. - The stability curves of all the slurries (figs. 3 and 4) were plotted as time against a settling ratio h_t/h_0 , where h_t is the metal-liquid-phase height at time t and h_0 is the total liquid-slurry height at zero time.

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Blow-out velocity. - A comparison of the blow-out velocities of all the fuels is shown in figures 5 and 6 where blow-out velocities are plotted against equivalence ratio. Each data point was found by fixing the fuel-flow rate and then increasing the air-flow rate until flame failure occurred. When the fuel-flow rates were set to give mixtures slightly richer than the lean limits (minimum fuel-air ratio for supporting combustion) shown in the figure, the blow-out velocity occurred below the lower limit of the scale of the air rotameter (shown by dot-dash line). It was concluded that the curves drop sharply at their lean end although the data points do not always clearly define this trend.

Slurries of fuel oils 5 and 6 with 13- and 2-micron powders could not be burned under the same conditions that the other slurries were burned. It was found that if these slurries were preheated in the spray-gun container to a temperature approaching 212° F, they could be burned and their blow-out velocities could be measured. In an unsuccessful effort to render these burnable without preheating, 5 percent heptane was added to the fuel-oil-6 slurry with enough petrolatum to restore the original viscosity.

Each fuel oil burned without preheating. The blow-out velocities of fuels oils 4 and 4A (fig. 5) were equal to or higher than those of fuels oils 5 and 6. The lean limits of fuel oils 4 and 4A were slightly lower than those of oils 5 and 6. Also shown are the blow-out velocity data for JP-4 fuel taken from reference 5. It is seen that the JP-4 fuel differs from fuel oils 4 and 4A only in a lower lean limit.

Slurries made with JP-4 and 13-micron powder and stabilized with petrolatum and gel had a higher blow-out velocity than those made with fuels oils 4 and 4A and the same powder (fig. 6). Photographs were taken of the sprays from the atomizing nozzle for the 13-micron-powder slurries made with fuels oils 4 and 4A and with JP-4 stabilized with gel and petrolatum (fig. 7). The sprays were all taken at the gun pressure at which the combustion tests were made, 16 pounds per square inch gage, and a fuel flow of approximately 0.2 pound per minute. It is seen that the fuel-oil-slurry sprays were much more finely atomized than the gel or petrolatum slurries. Therefore, the lower performance of the fuel-oil slurries cannot be attributed to spray characteristics, but more likely to lack of a low-boiling fraction in the hydrocarbon.

The effect of the thixotropic properties (diminishing viscosity with increasing shear rate) of the gel slurry is shown in figure 7(c) where it is seen that the spray droplets were much smaller than those of the petrolatum slurry (fig. 7(d)) in spite of the much higher viscosity of the gel. The blow-out velocity of the preheated fuel-oil-5 slurry was not different from the blow-out velocities of unheated slurries containing fuels oils 4 and 4A. The blow-out velocity was lower and the lean limit higher for the fuel-oil-6 slurry.

The blow-out velocities for the slurries with 2-micron powder in fuel oils 4, 4A, and 5 were for the most part above the upper limit of the air-flow capacity of the apparatus. The data points with vertical arrowheads indicate that the maximum air flow of the apparatus did not bring blow-out. It is seen that the 2-micron magnesium gave lower lean limits than the coarser powder. This trend toward improved combustion properties with decreasing particle size indicates a higher reactivity of magnesium with increase in surface area. Improved combustion properties with decreasing particle size were reported in reference 5. A similar effect was also noted in reference 1 where it was found that the rich and lean combustion limits were extended by increasing the metal concentration of magnesium slurries.

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Combustion efficiency. - The combustion efficiencies of the magnesium in 13-micron-magnesium slurries made with fuel oils 4, 4A, 5, and JP-4 stabilized with gel and in a 2-micron-magnesium slurry made with fuel oil 4A are shown in figure 8. The efficiency of the 13-micron powders was not appreciably affected by the carrier. The 2-micron powder gave a somewhat higher efficiency in spite of its being burned at an inlet-air velocity of 80 feet per second instead of the 20 feet per second used with the 13-micron slurries. The viscosities of the four 13-micron-powder slurries covered a range from 22 to 22,750 centipoises. The viscosities seem to have had little, if any, effect on the combustion efficiencies in the $1\frac{7}{8}$ -inch-diameter burner.

The combustion efficiency of the hydrocarbon in each of the slurries is apparently unaffected by boiling range, hydrogen-carbon weight ratio, or magnesium-powder size (fig. 9).

SUMMARY OF RESULTS

The following results were obtained in an experimental investigation conducted with a $1\frac{7}{8}$ -inch-diameter burner to determine the suitability of residual fuel oils as carriers in magnesium slurries:

1. The slurries made with 13-micron-powder and the two more viscous residual fuel oils were stable for at least 3 weeks, but they could not be burned in the test burner without preheating.
2. The two slurries containing the less viscous fuel oils did not provide sufficient stability for the 13-micron powder, but the combustion efficiency was comparable to JP-4 slurries.

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3. All the residual fuel oils burned satisfactorily in a $1\frac{7}{8}$ -inch ram-jet-type combustor using air atomization without preheating.

4. The blow-out velocities of the fuel-oil slurries were lower than those of the petrodatum- or gel-stabilized JP-4 slurries.

5. Fuel-oil slurries of 2-micron powder had much higher blow-out velocities than fuel-oil slurries made with 13-micron powder.

6. All the 13-micron-magnesium-powder slurries with fuel oil or JP-4 as carriers had substantially the same metal and hydrocarbon combustion efficiencies over a range of equivalence ratios. The 2-micron-powder slurry, although burned at four times the inlet-air velocity of the 13-micron-powder slurries, showed a slightly higher combustion efficiency of the metallic constituent.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 16, 1953.

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4. Lord, Albert M.: An Experimental Investigation of the Combustion Properties of a Hydrocarbon Fuel and Several Magnesium and Boron Slurries. NACA RM E52B01, 1952.
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TABLE I. - CARRIER FLUID PROPERTIES

Properties	MIL-F-5624A Grade JP-4	Fuel oil			
		Number 4A	Number 4	Number 5	Number 6
Initial boiling point, °F	140	395	444	350	404
Percent evapo- rated					
5	199	430	484	510	564
10	222	438	499	553	602
20	248	450	517	607	639
30	268	461	532	641	654
40	286	474	551	658	664
50	300	487	572	(a)	(a)
60	325	501	604		
70	348	518	646		
80	382	540	676		
90	427	571	(a)		
95	459	603			
Final boiling point	488	647			
Residue, percent	1	1.8			
Reid vapor pressure, lb/sq in.	2.5	Negli- gible	Negli- gible	Negli- gible	Negli- gible
Specific gravity at 60° A.P.I.	52.8	31.3	27.7	15.7	13.7
Specific gravity at 60° F/60° F	0.768	0.869	0.889	0.961	0.975
Hydrogen-carbon ratio	.167	.139	.145	.124	.123
Heat of combustion, Btu/lb	18,675	18,260	18,130	17,580	17,480

^aDistillation incomplete because of cracking.

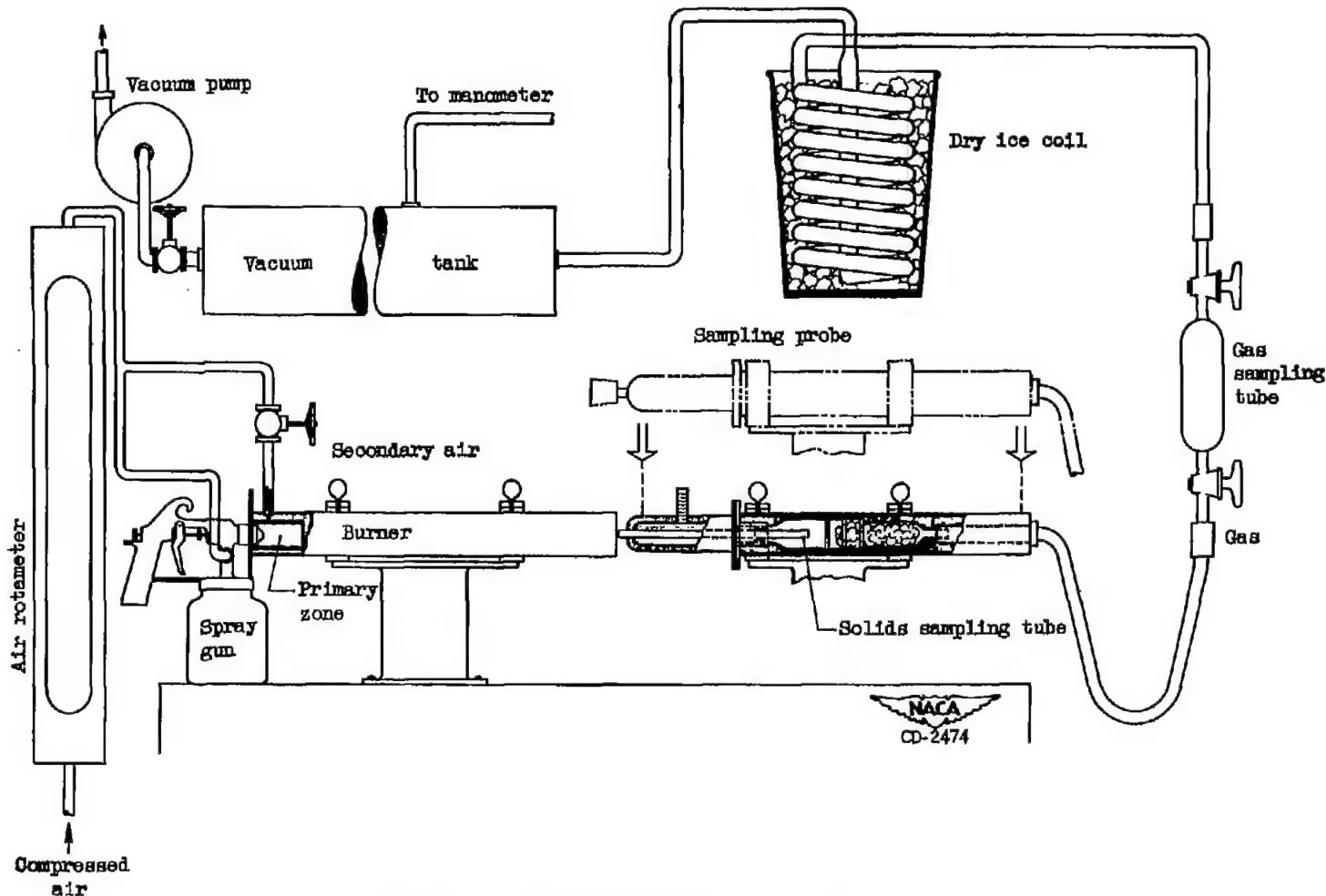


Figure 1. - Slurry burner and sampling apparatus.

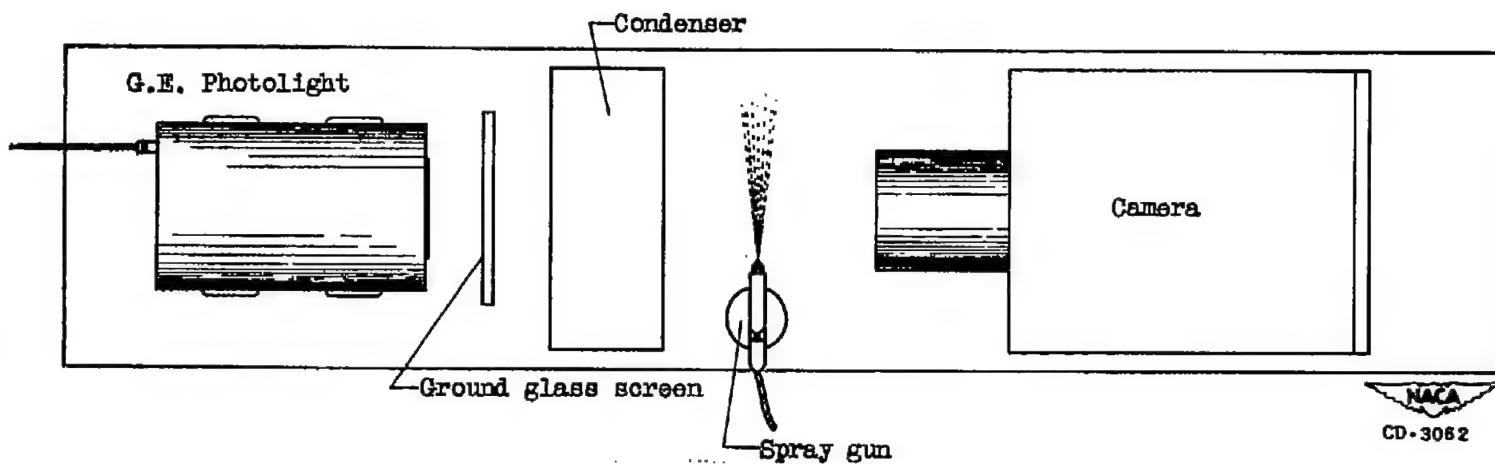
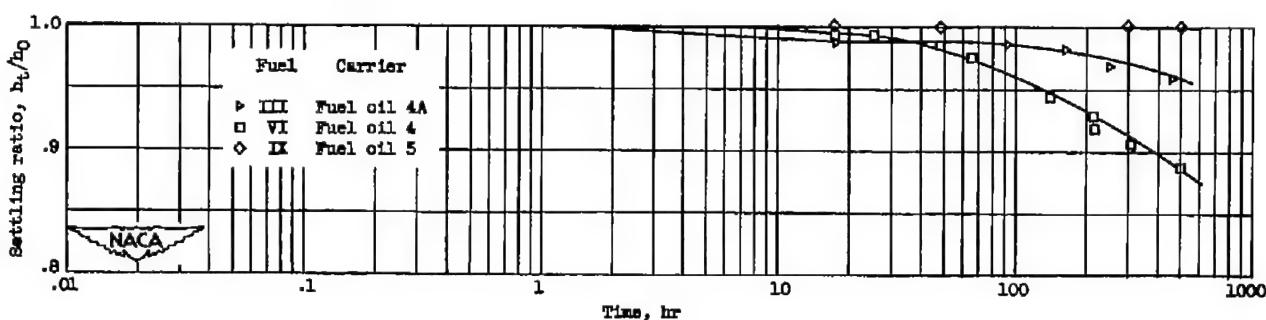
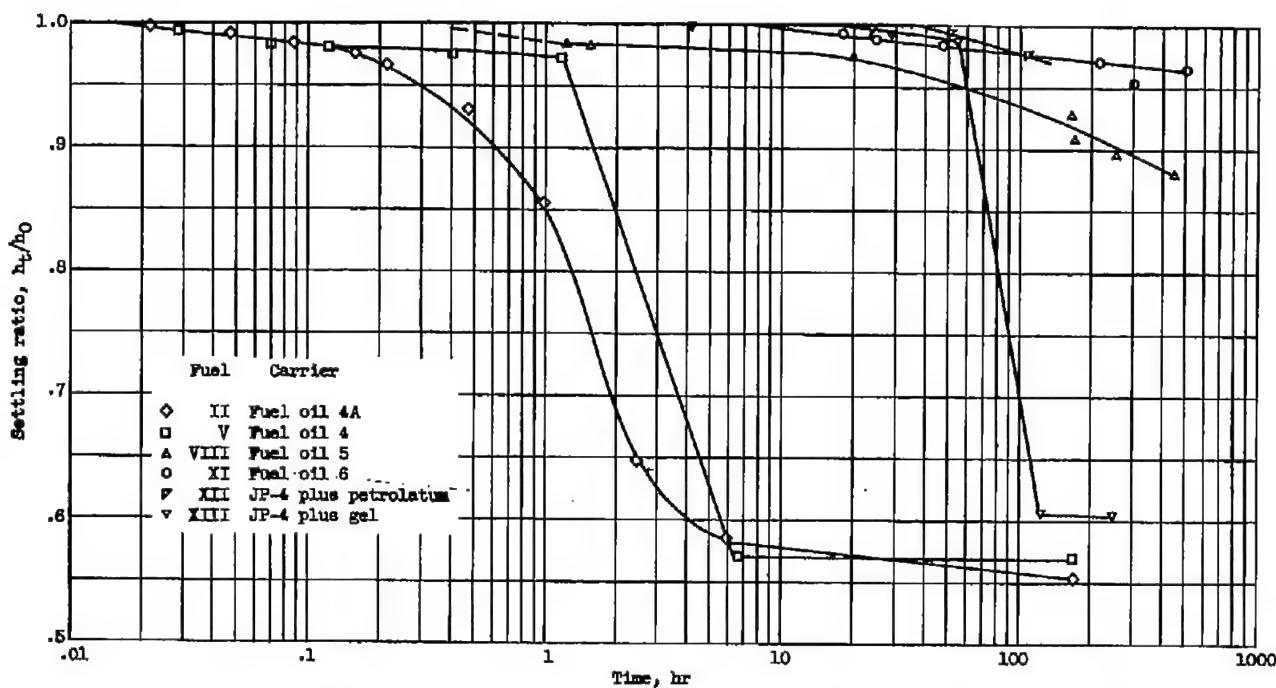


Figure 2. - Setup for photographing spray droplets.



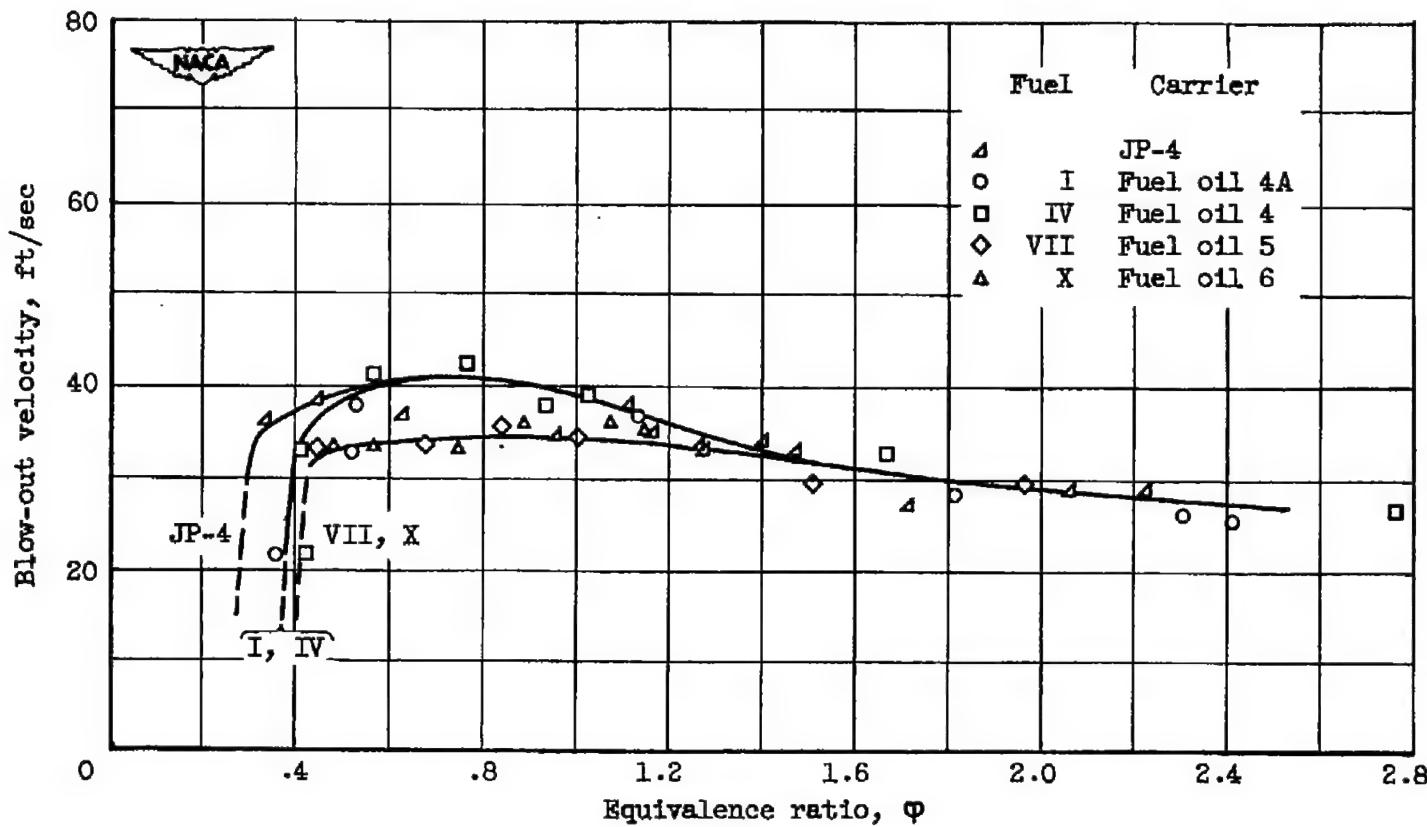


Figure 5. - Comparison of blow-out velocities of several hydrocarbons.

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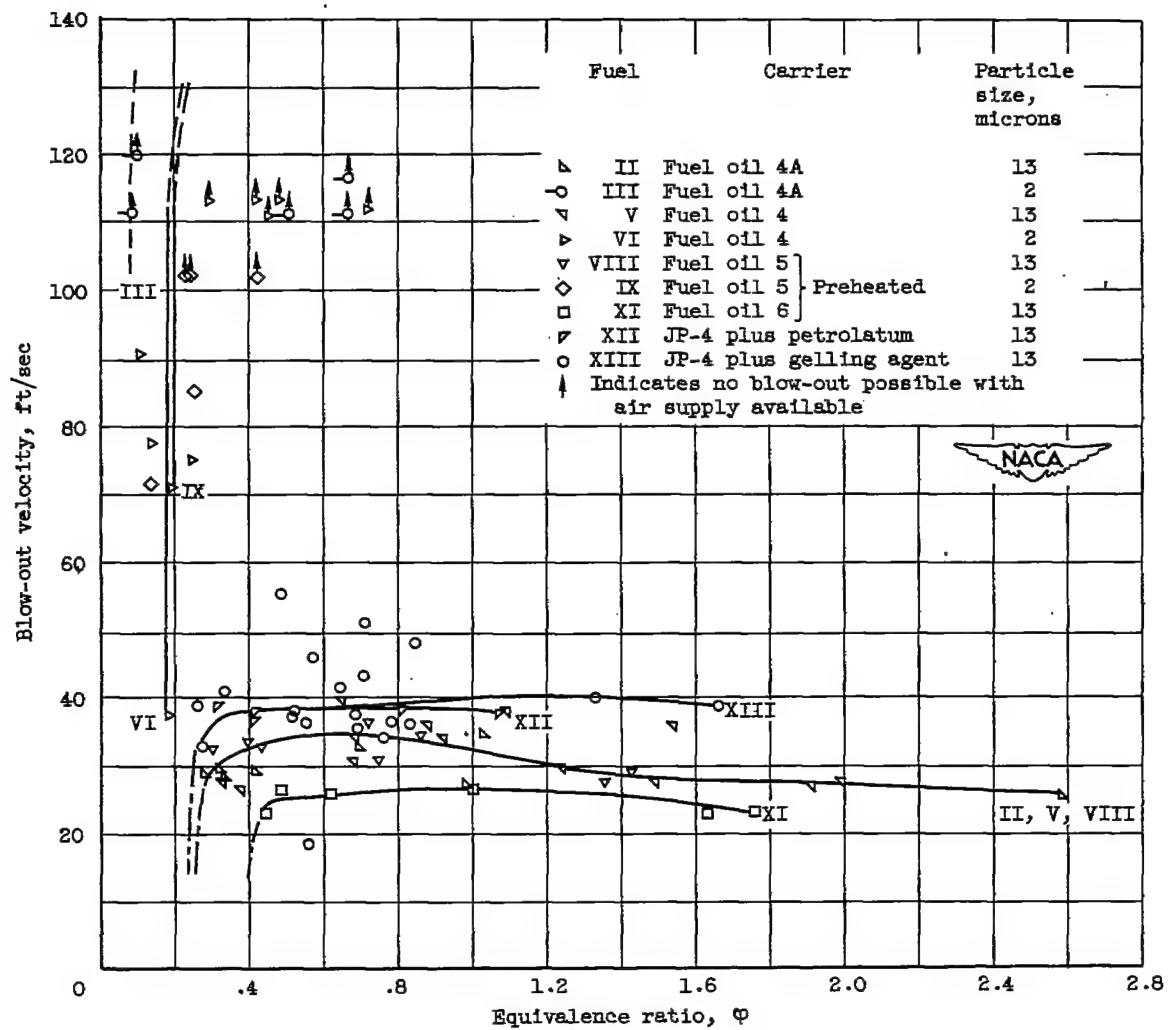
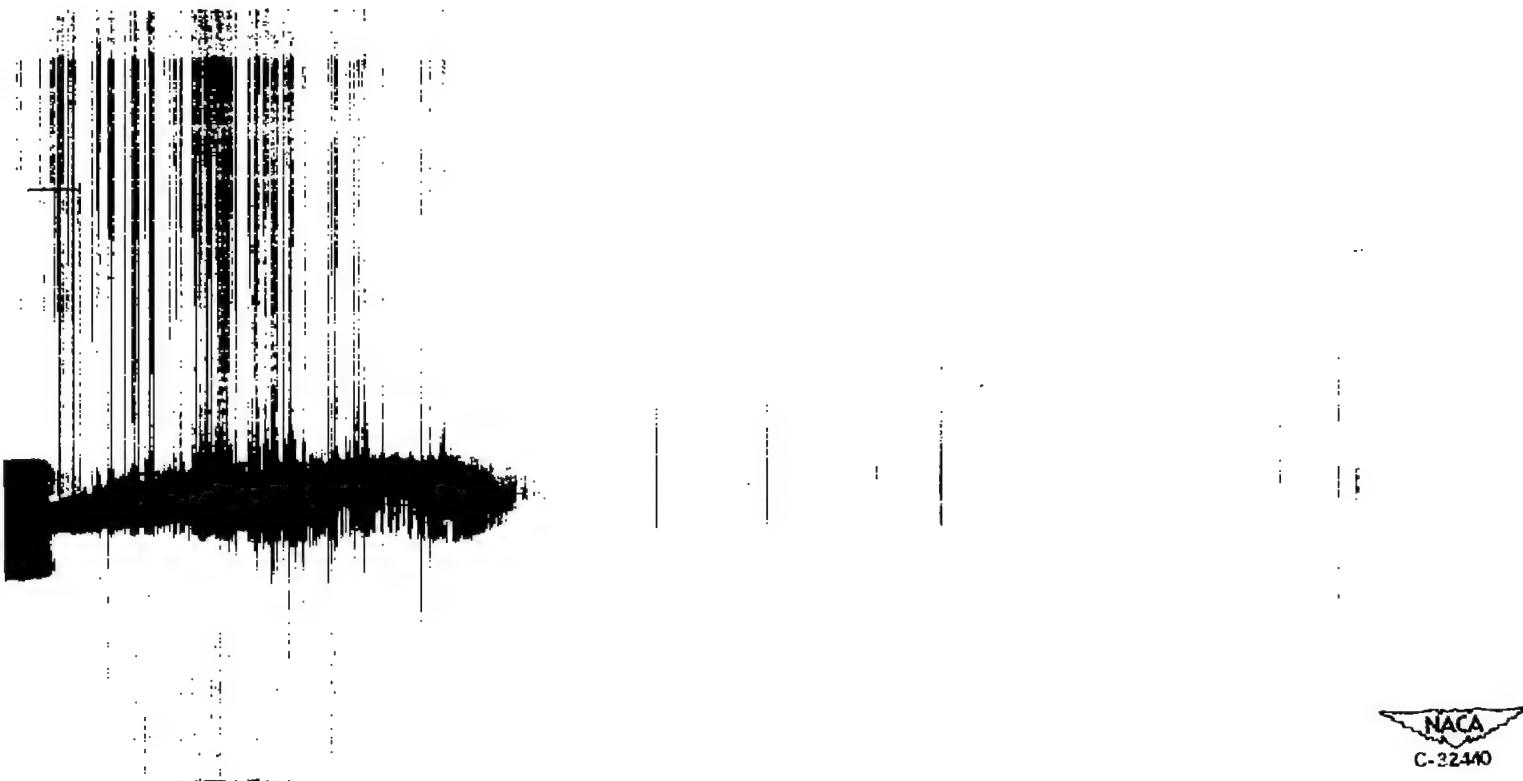


Figure 6. - Comparison of blow-out velocities of 50 percent by weight 2- and 13-micron, magnesium slurries in several hydrocarbons.



(a) Fuel III, fuel oil 4A plus 50 percent by weight 13-micron magnesium; viscosity, 22 centipoises at 30° C.

Figure 7. - Photographs of spray from atomizing nozzle.



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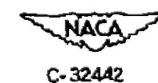
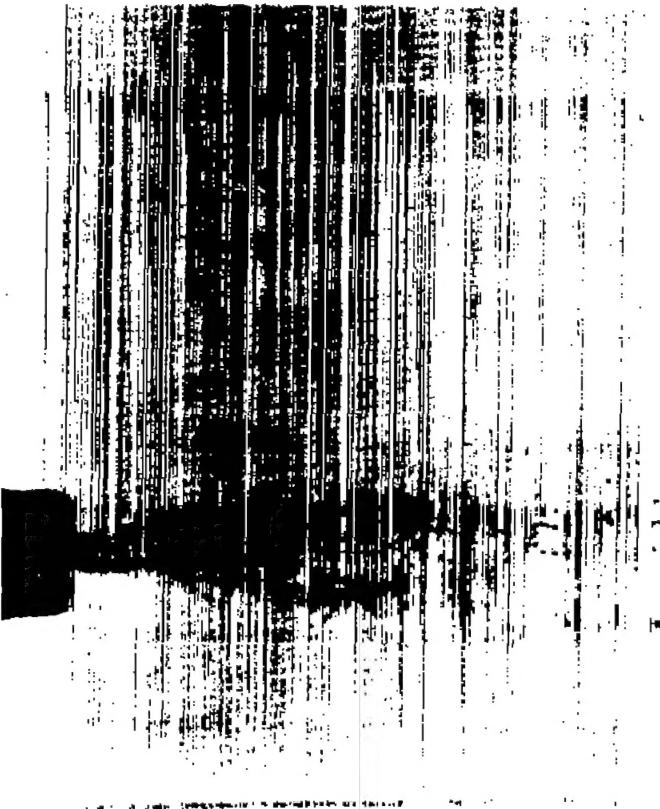
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(b) Fuel V, fuel oil 4 plus 50 percent by weight 13-micron magnesium; viscosity, 75 centipoises at 30° C.

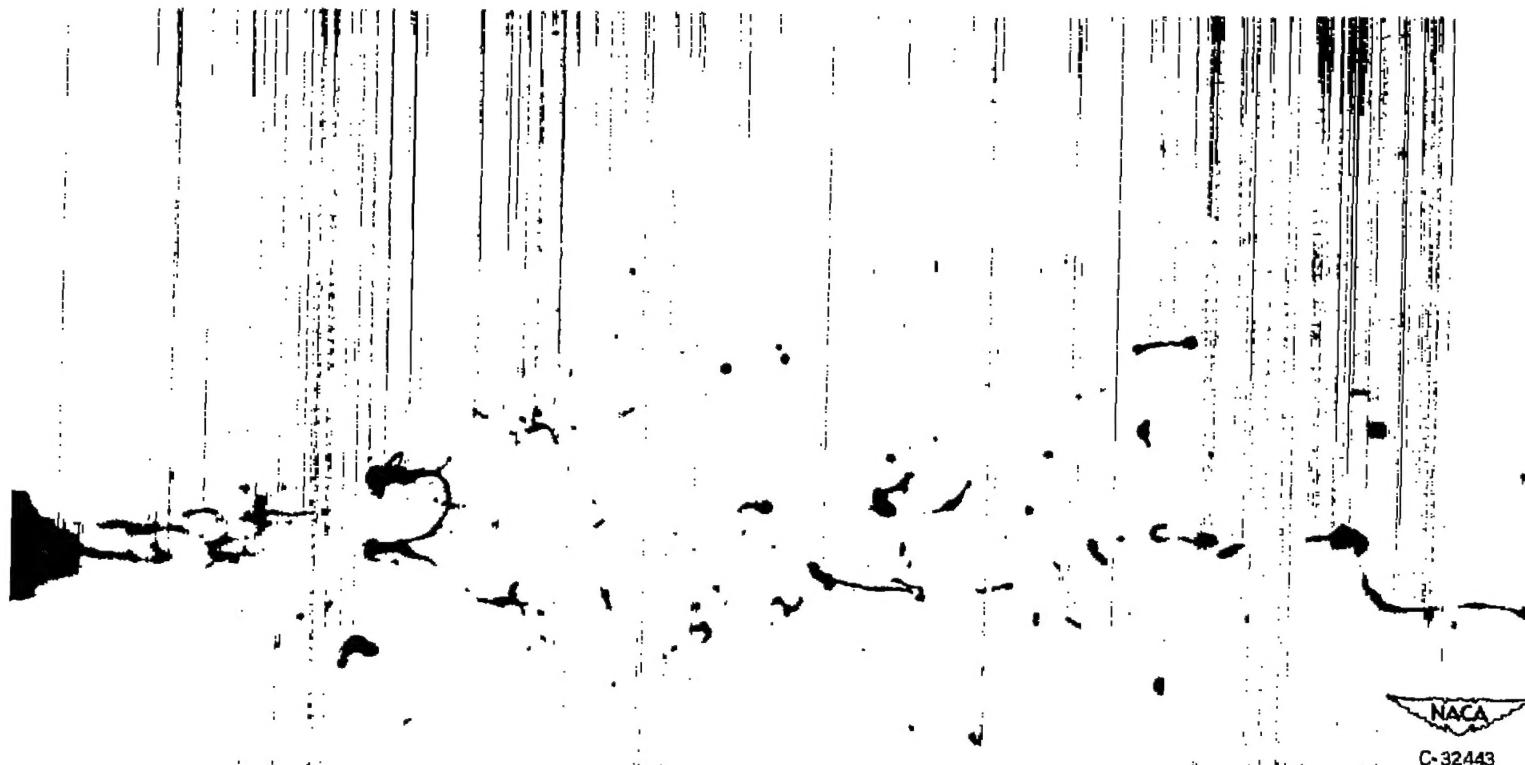
Figure 7. - Continued. Photographs of spray from atomizing nozzle.



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(c) Fuel XII, 50 percent by weight 13-micron magnesium in MIL-F-5624A grade JP-4 fuel plus 0.4 percent-gel; viscosity, 22,750 centipoises at 30° C.

Figure 7. - Continued. Photographs of spray from atomizing nozzle.



(d) Fuel XIII, 50 percent by weight 13-micron magnesium in MIL-F-5624A grade JP-4 plus 24 percent petrolatum; viscosity, 4000 centipoises at 30° C.

Figure 7. - Concluded. Photographs of spray from atomizing nozzle.

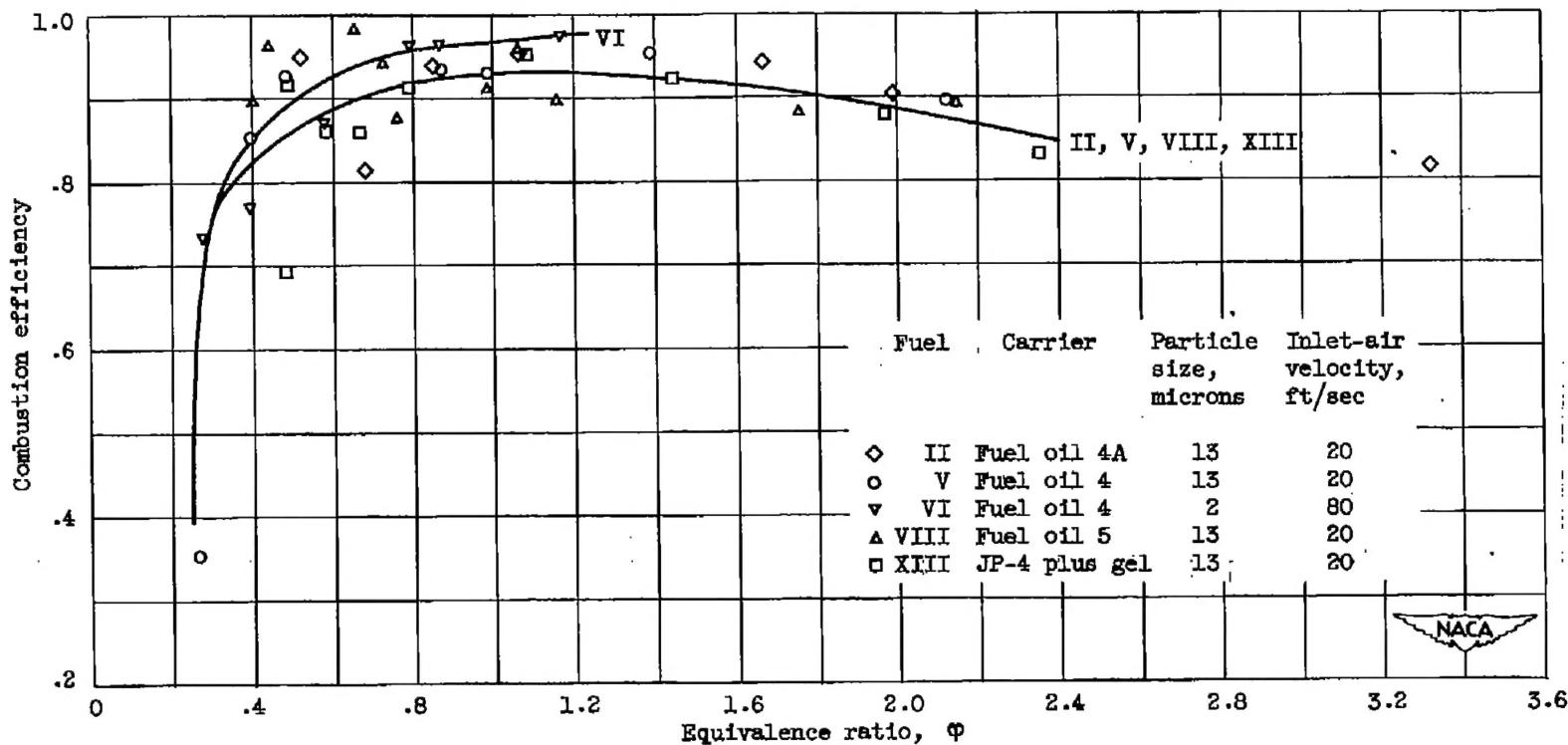


Figure 8. - Combustion efficiency of magnesium in several slurries.

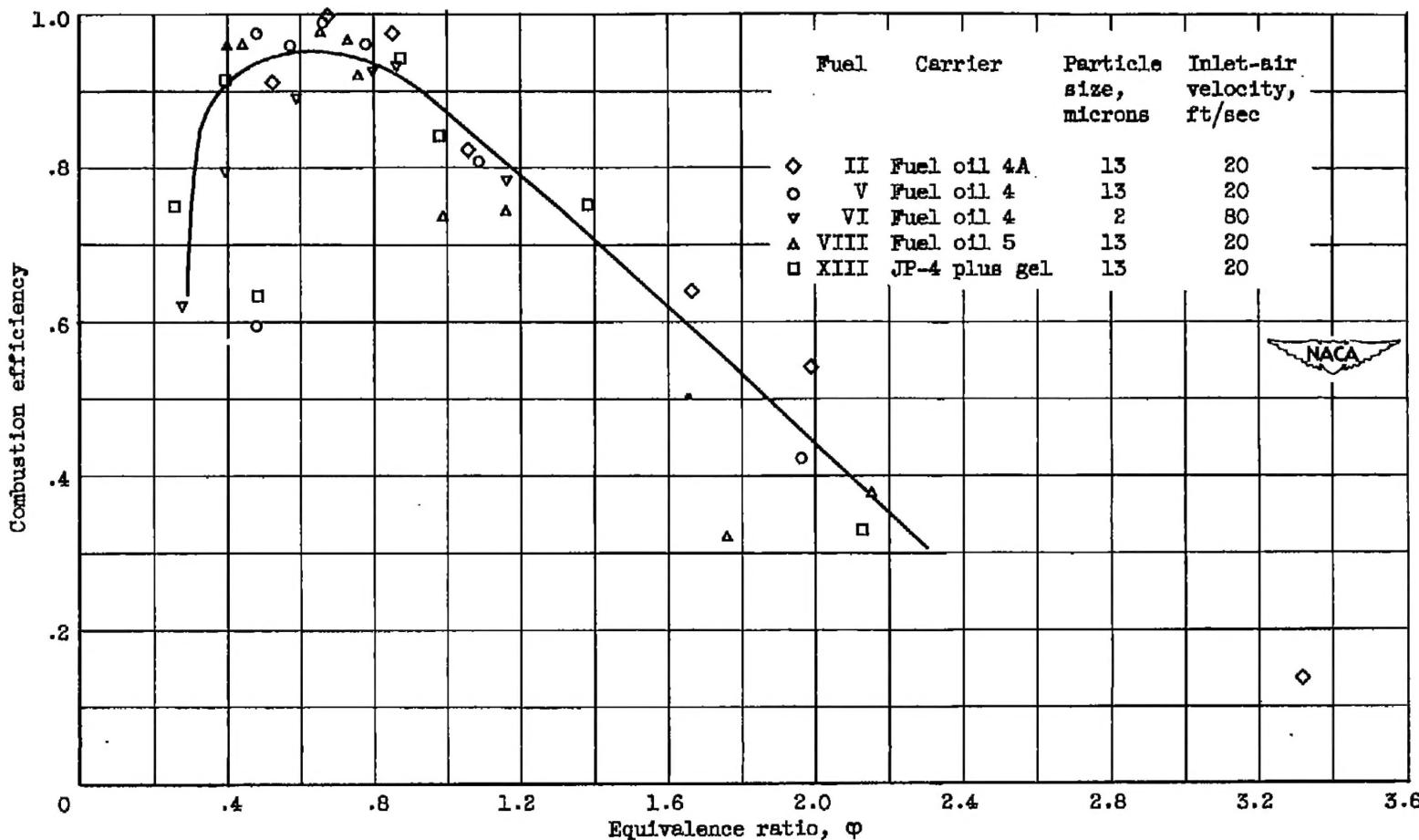


Figure 9. - Combustion efficiency of hydrocarbon in several slurries.